

II-1. Reservoir and River Stage Exceedance Probabilities

Key Concepts

Often the level of the reservoir, or water surface stage, is a key loading parameter for evaluating a potential failure mode. Probabilities for branches that follow water surface stage in the event tree are often conditional on the magnitude of the load. Since the forces acting on a structure are generally proportional to the height of the water squared, the probability of failure typically varies with the water surface stage. Consequences are also influenced by the water surface stage and other related parameters such as reservoir volume. Consequences may be low to moderate below a certain stage (e.g. top of active storage), but could increase rapidly above that stage due to increased discharge releases. The probability of attaining a given range in reservoir elevation can therefore be an important consideration in performing a risk analysis.

Reclamation and USACE have readily available water surface stage data for most of their dams. Levee data may not be as readily available but can often be obtained from USGS gage records or other sources. The period of record and collection interval for the data varies.

The period of record data can be used to infer the probability of future water surface stages. The data should be reviewed to verify that the period of record is representative of current operating conditions. If there has been a change in operation somewhere during the record, this must be identified and only data consistent with the expected future operation used in the evaluation. For example, a non-native shrimp seems to have found its way into a reservoir. In order to prevent the shrimp from finding their way downstream over the uncontrolled spillway, the reservoir has been operated at lower levels for the past couple of decades. Reservoir data from previous years would not represent the future expected operations without some adjustment.

The data collection interval (e.g. hourly, daily average, once per day at a particular time) should be considered because daily average values can sometimes dampen flood peaks and data collected at a particular time of day can miss flood peaks altogether. For many Reclamation and USACE facilities, daily average data is adequate and the available data is often converted to a daily time interval.

Use of Exceedance Curves

Reclamation develops separate potential failure modes (PFMs) for different loading categories. In other words, there are normal operation (static) PFMs, hydrologic PFMs, and seismic PFMs. In some cases, a given failure mechanism (say, internal erosion through the embankment) may be evaluated for each of the three loading conditions. With this type of categorization, historical normal reservoir operating levels are utilized



for static PFMs, while hydrologic PFMs require flood frequency curves that provide the exceedance probability of a given reservoir water surface.

USACE evaluates PFMs over the full range of hydrologic loading, from normal operations through various flood loadings. USACE exceedance curves include both normal operations as well as projected flood-induced levels.

The fundamental difference in the two agencies' approaches is simply this: Reclamation reservoir exceedance curves are based solely on historic recorded reservoir level data, while USACE exceedance curves also include expected levels resulting from floods.

Additional discussion about the different uses is presented below.

Use of Reservoir Exceedance Curves in Risk Analysis – Reclamation Approach

The data to be used in the reservoir exceedance evaluation is dependent on the potential failure mode to be evaluated, such as static, seismic or hydrologic.

- For static potential failure modes, such as seepage and internal erosion modes that could occur under normal operations, the estimates are annualized by considering the likelihood that the reservoir will rise to a specified level in any given year. Thus, only the maximum values for each year of record are used in the evaluation, as it is most likely that an internal erosion failure would take place with a nearly full pool.
- For seismic potential failure modes, the estimates are annualized by the seismic load probability, and the postulated earthquake(s) could occur at any time during the year. Therefore, it is desired to know the chances of the reservoir being at or above a certain level when the earthquake hits. For this evaluation, all of the data is used (typically daily reservoir elevations), and the percentage of time above a given elevation is used. It is important to note that these estimates are not annual probability estimates, but simply the percentage of time the reservoir has exceeded user-defined elevations. To be clear, a reservoir percentage of time curve is not a probability curve, because elevations are correlated between successive time intervals, and elevation characteristics are dependent on the season of the year (see, e.g. Mosley and McKerchar, 1993 p. 8.27 and Salas, 1993).
- Flood-related potential failure modes could require even a different approach. For example, if the critical floods seem to be general storm rain-on-snow events, flood season could occur for a few months in the spring of the year. The starting reservoir elevation could be critical to the results of flood routings (maximum reservoir elevation) for a given flood loading range. Therefore, the likelihood of exceeding certain starting reservoir elevations when the flood occurs could be important, and only reservoir elevations during flood season are used in the evaluation.

Use of Exceedance Curves in Risk Assessment – USACE Approach

Water surface stage (reservoir pool level for dams or river elevation for levees) and its associated probability of occurrence is a key parameter used to define the loading

conditions for a dam or levee risk analysis. For flood loading, the exceedance probability for water surface stage is used as the basis for annualizing the risk estimate. For seismic loading, the exceedance duration for water surface stage is used to evaluate the outcome of a particular stage coincident with the earthquake.

Record data of reservoir levels forms the basis for that portion of the reservoir exceedance curve that deals with relatively frequent annual probabilities. Extrapolation of the period of record data to stages higher than those previously observed is usually required. This can be accomplished by routing hydrographs using information from the hydrologic hazard analysis.

Other parameters that may be related to water surface stage (e.g. discharge, velocity, volume, or duration) can also be important. These parameters can be considered in the risk analysis by implicitly associating a representative hydrograph or other related piece of information with its corresponding water surface stage. An explicit approach can also be implemented by including the additional parameters in the event tree along with their associated probabilities.

Development of Exceedance Curves

Because the two agencies consider the effect of reservoir level differently in their analysis of risk of potential failure modes, the USACE and Reclamation reservoir exceedance curves are unique and are thus developed differently. The following section details the procedures used by each agency to develop these curves.

Reclamation Approach for Developing Reservoir Exceedance Curves

Procedure for Developing the Exceedance Curve

The following steps are typically followed in developing reservoir level exceedance curves.

- The first step is to collect the reservoir level data in terms of date and associated reservoir elevation. Each Region is a little different in how this information is accessed. Most of the data can be accessed through the intranet or internet. For some Regions, like the Great Plains and Pacific Northwest Regions, the data can be found with relative ease from their intranet sites, which access the Hydromet system. For the Mid-Pacific Region, you may be directed to state sites in order to find the information. It may take a little searching to find the information on some of the other Regional or Area Office web sites. Once the data is found, it is highlighted, copied, and pasted or imported into an Excel spreadsheet. Links to archive (period of record) reservoir data (as of March 2009) are:

GP Region Hydromet:

http://www.usbr.gov/gp/hydromet/hydromet_arcread.cfm

PN Region Hydromet: <http://www.usbr.gov/pn/hydromet/arcread.html>

LC Region: <http://www.usbr.gov/lc/riverops.html>

UC Region CRSP: <http://www.usbr.gov/uc/crsp/GetSiteInfo>

MP Region (via California Data Exchange Center):

Reclamation Approach for Developing Reservoir Exceedance Curves

<http://cdec.water.ca.gov/>

The key parameter of interest from the Hydromet system is “FB” (reservoir ForeBay elevation). A secondary parameter is AF (total storage in Acre-Feet) (sometimes called active storage), which can be used to estimate reservoir forebay elevation with a reservoir capacity-elevation table, if storage is reported instead of elevation.

- The electronic reservoir data may only extend back for a short period, e.g. back to 1986. If so, it may be important to look for additional data from prior years. One straightforward way to do this is to contact the Area Office where the dam is located via email (e.g. CVO, ECAO, etc.). The Area Office usually has reservoir data in electronic format that in many cases is not in various on-line databases. In some cases, such data can be found in the instrumentation data base at the Technical Service Center. The instrumentation plots typically only have a limited portion of the reservoir level data set, so it is important to search for all available data. In other cases, it may be necessary to obtain hardcopy records of reservoir level and enter the data manually.
- After data collection, it is important to determine the frequency of collection and data quality. At most sites, daily reservoir elevations and storages are collected. At some sites, only monthly (typically end of month contents) data are collected or reported. There may be seasonal interruptions in data collection as well. This is sometimes the case when an irrigation district makes measurements. Also, for high-elevation sites winter records can be fragmentary or incomplete due to ice and snow effects. Check the last Comprehensive Review (CR) report and make sure the historical high reservoir level is in the data base. Usually the daily reservoir levels are taken at a certain time each day, and may miss the peaks if the reservoir is rapidly rising or falling. This may be important if the reservoir storage volume or surcharge volume is small in relation to the drainage area of the watershed, or has no carry-over storage from one year to the next.
- Plot the reservoir elevation vs. time as a series of single data points (no line – see Figure II-1-1). Review the plot, looking for missing data and sudden shifts. Sudden shifts might be due to a datum change, in which case an adjustment will need to be made to some of the data. Other abnormalities, such as typos and missing or bad data should also be corrected or deleted from the data. Note the percent of the corrected record that is complete.

Reclamation Approach for Developing Reservoir Exceedance Curves

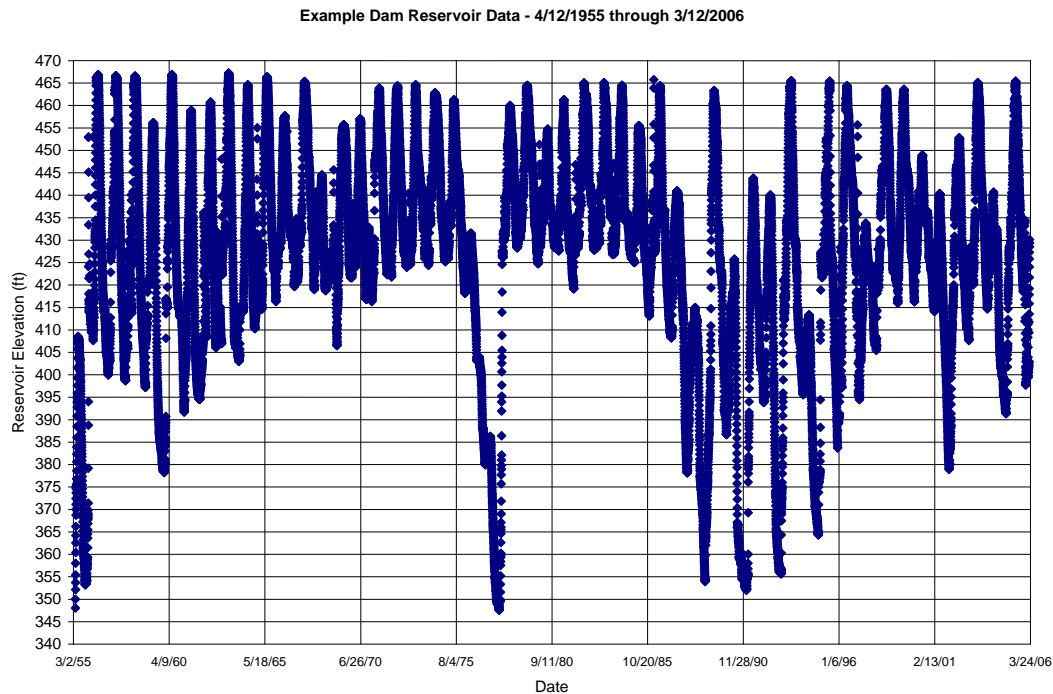


Figure II-1-1 – Time Series Plot of Reservoir Elevation

- Find the minimum and maximum reservoir levels in the data to determine the range over which the plots need to be made. Then choose a calculation interval. Calculations are typically done every foot, but for smaller dams or dams where the reservoir doesn't fluctuate a lot, this could be taken as a smaller interval. Similarly, for high dams with significant reservoir fluctuation, a larger interval might be chosen.
- For seismic potential failure modes, set up the spreadsheet to perform the exceedance probability calculations for each reservoir level according to the increment selected above. This is done, for example, using the following Excel function:

$$=(18598-(18598-\text{COUNTIF}(\$C\$1:\$C\$18598,">353")+1))/((18598+1)*100$$

where there are 18,598 reservoir elevations contained in column "C" of the spreadsheet from rows 1 to 18,598, and the reservoir elevation for which the exceedance likelihood is being calculated is 353. A similar calculation is performed for each reservoir elevation increment. A similar approach can be used for reservoir levels to be used for evaluating "flood season" loadings. However, only those reservoir elevations for the months of interest are extracted from the data and used in the analysis.

- For static potential failure modes, it is necessary to extract the maximum reservoir elevation for each year and store the data in a separate spreadsheet list. This can be done manually, or a spreadsheet routine can be written to do it. The calculations can be performed in a manner similar to that described in the

Reclamation Approach for Developing Reservoir Exceedance Curves

previous bullet. Alternatively, the data can be sorted in order of ascending reservoir elevation. Then, for example if there are 51 years of record, and the rank of the maximum annual reservoir level is sorted in column “G” of the Excel spreadsheet (from lowest to highest), the exceedance probability for the reservoir level in row 6 is calculated as (for a Weibull plotting position):

$$=(51-G6+1)/(51+1)$$

- Example plots for exceedance probability and annual exceedance probability are shown in Figures 8-2 and 8-3, respectively.

**Example Dam Reservoir Data - 4/12/1955 through 3/12/2006
Percentage of Time Exceedance for Seismic and Hydrologic Risk Analysis**

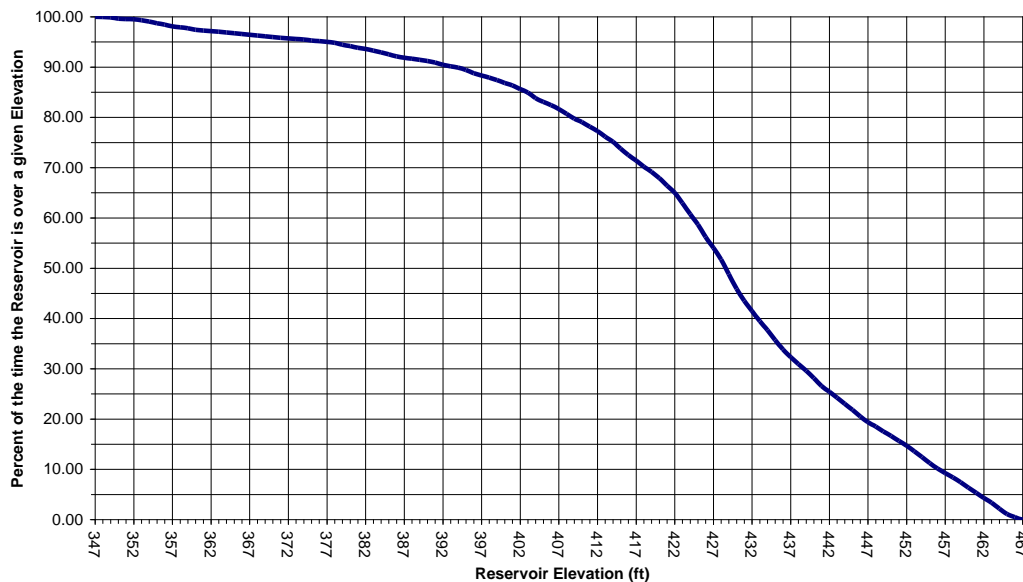


Figure II-1-2 – Example Reservoir Percentage of Time Exceedance Plot

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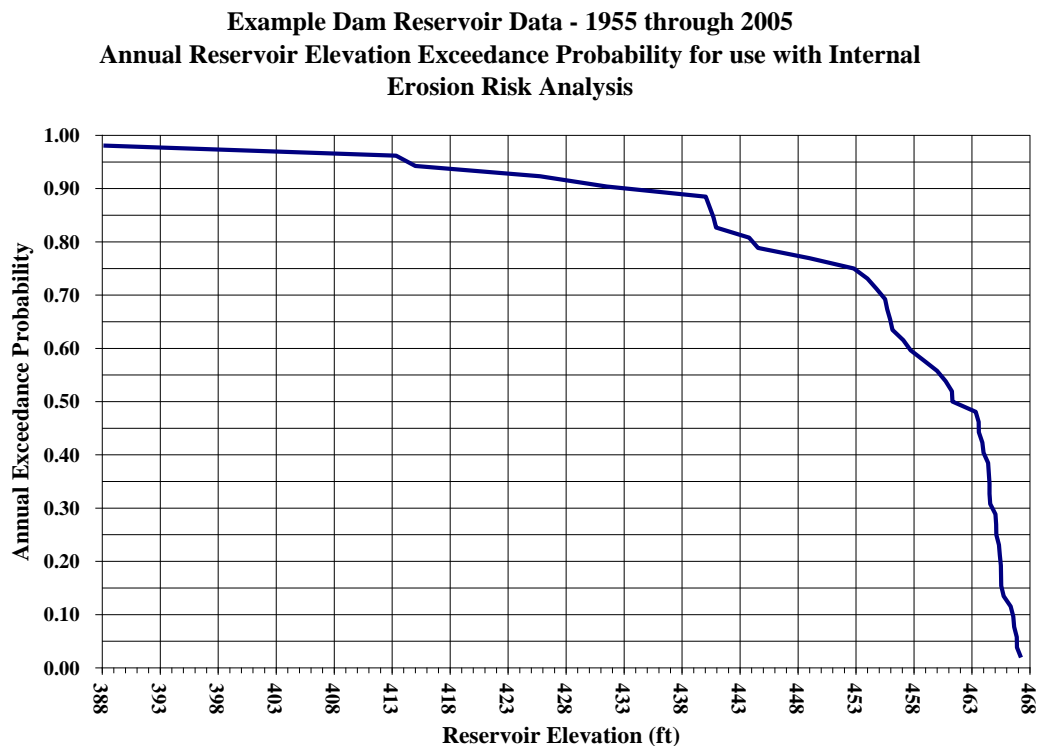


Figure II-1-3 – Reservoir Annual Maximum Exceedance Probability Curve

Calculating Reservoir Load Range Probabilities

The event tree method of estimating risks, as adopted by Reclamation, requires the loadings to be divided into discrete ranges. This applies to reservoir load ranges as well as seismic and flood load ranges. The probability of being in a given reservoir range is the exceedance probability of the lower reservoir elevation for the range minus the exceedance probability of the upper reservoir elevation for the range. For example, from Figure II-1-3, the probability of annually reaching a level between elevations 453 and 463 is approximately $0.75 - 0.48 = 0.27$.

Handling Uncertainty

To date, Reclamation has not put uncertainty bounds on reservoir exceedance curves. Thus, only expected values are used in event tree analyses. However, uncertainty bounds could possibly be developed by plotting exceedance curves for each year, and then performing a statistical evaluation for each reservoir elevation or range to estimate confidence intervals. This type of information could be used with seismic or hydrologic potential failure modes. For static potential failure modes, it may be possible to fit a function to the “ratio of years” exceedance curves for the period of record, and then use the statistics of the function to develop confidence intervals. Procedures to estimate uncertainty bounds are being considered.

Reclamation Approach for Developing Reservoir Exceedance Curves

Considerations for Comprehensive Reviews

If reservoir exceedance plots are not already available, they typically would not be developed for a Comprehensive Review (CR). Instead, a time plot of reservoir level, typically included with most instrumentation plots, would be reviewed, and needed reservoir exceedance probabilities would be estimated from the approximate number of spikes (annual exceedance probability) or area of the curve (exceedance probability) above each reservoir level of interest.

USACE Approach for Developing Exceedance Curves

Similar concepts and methods are used for both dams and levee when estimating exceedance curves. The primary difference is that water surface profiles are rarely needed for dams but are usually needed for levees. When needed, water surface profiles can be developed using software packages such as HEC-RAS.

Binomial Distribution

Random variables associated with floods are commonly modeled using the binomial probability distribution. The distribution is based on a series of discrete trials (e.g. annual) with two possible outcomes for each trial (e.g. flood or no flood). The probability for occurrence of the event is assumed to be constant and each trial is assumed to be statistically independent. The equation for the binomial distribution can be used to estimate the probability of obtaining exactly n successful outcomes (e.g. the flood occurs) out of N trials given the probability of success for an individual trial is p .

$$P_p(n|N) = \frac{N!}{n!(N-n)!} p^n (1-p)^{N-n}$$

As an example, the binomial distribution can be used to estimate the probability that someone living within the 100 year floodplain will experience at least one flood during a 30 year mortgage period. The solution is simplified by solving for the complement of no floods occurring.

$$\begin{aligned} P_p(n \geq 1 \text{ Flood} | N = 30 \text{ Years}) &= 1 - P_p(n = 0 \text{ Flood} | N = 30 \text{ Years}) \\ &= 1 - \frac{N!}{0!(N-0)!} p^0 (1-p)^{N-0} \\ &= 1 - (1-p)^N \\ &= 1 - (1-0.01)^{30} \\ &= 0.26 \end{aligned}$$

Exceedance Probability

When evaluating risks associated with flood loading it is necessary to consider the probability that the water surface will reach a particular stage within a given period of time. This is accomplished using an exceedance probability relationship that characterizes the likelihood that a random variable (e.g. peak water surface stage) will exceed a particular value over a given time period (e.g. one year). Risk analyses for dam and levee safety typically evaluate floods on an annual basis using the maximum stage obtained during a given year. Other approaches can be taken

USACE Approach for Developing Exceedance Curves

using different time periods (e.g. seasonal) and different flood parameters (e.g. discharge, velocity) if needed to represent the flood loading characteristics at a particular site.

Annual exceedance probability relationships can be developed from a combination of period of record information and synthetic events generated from the hydrologic hazard information.

Period of Record Analysis

The first step in developing an exceedance probability relationship involves collecting, assembling, and reviewing the period of record data. Plotting the data can assist with evaluating data quality. An example data set showing daily average reservoir stages for a dam is presented in Figure II-1-4. For this example, it is assumed that daily average values are appropriate for the risk analysis and that the risk analysis is based on ‘normal’ operating conditions. Adjustments to the data time interval are not needed in this case. The plot, however, reveals several potential data quality issues. The time periods associated with the initial reservoir filling, the dam safety emergency, and the pool restriction for interim risk reduction may not be representative of normal operation. Some of the data also appears to be missing and incorrect based on a visual inspection of the plot.

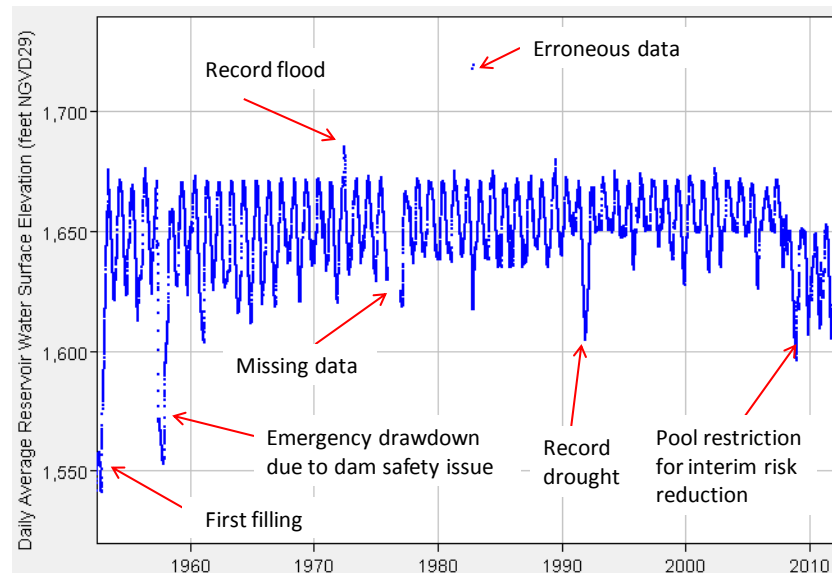


Figure II-1-4. Daily Average Reservoir Stage Data

The full period of record should be considered for the exceedance probability relationship unless there are significant issues with the data not being representative of the operating conditions assumed for the risk analysis. The maximum water surface stage obtained each year (annual peaks) needs to be extracted from the daily data. The data extraction can be based on calendar year, water year, or some other interval appropriate for the site.

Assuming the risk analysis for the example dataset is based on a normal operating condition, a decision is made to exclude periods associated with the first filling, dam safety emergency, and pool restriction. The adopted period of analysis includes calendar years 1953-1956 and 1959-2007. Annual maximum water surface elevations are extracted for each calendar year in the period of analysis and the results are presented in Figure II-1-5.

USACE Approach for Developing Exceedance Curves

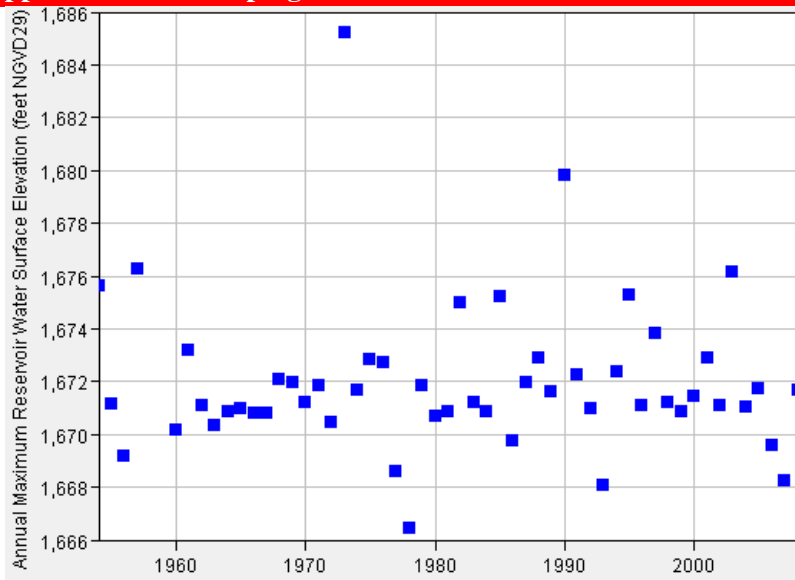


Figure II-1-5. Annual Peak Reservoir Stage Data

The exceedance probability relationship is then computed by sorting the annual peak data for the adopted period of analysis in descending order, ranking the sorted data from 1 to n, and computing the annual exceedance probability (AEP) for each data value using the following equation where M is the rank and n is the total number of values.

$$AEP = 100 \frac{M}{n + 1}$$

Note that the weibull plotting position formula is used in this example, but other plotting position formulas can be used. A plot of the resulting exceedance probability relationship is presented in Figure II-1-6.

USACE Approach for Developing Exceedance Curves

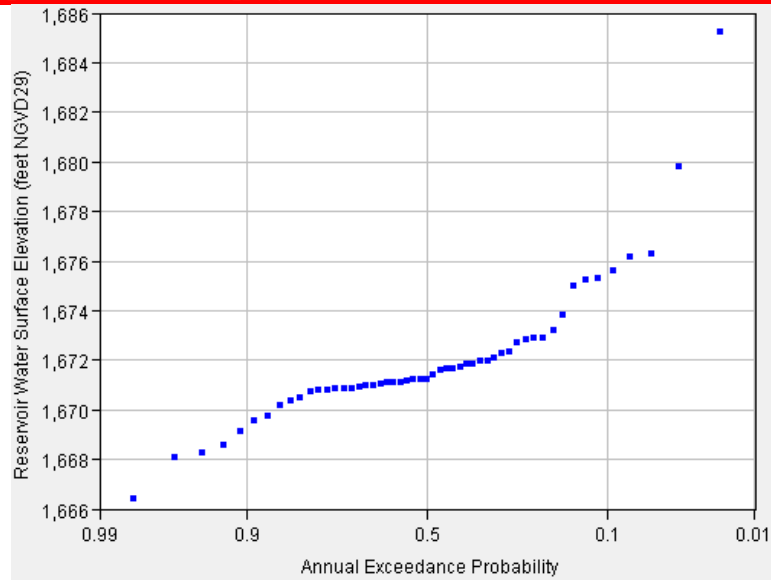


Figure II-1-6. Exceedance Probability Relationship

Partial Duration Series

The binomial distribution assumptions (statistically independent trials) are not always valid particularly for relatively frequent events with an annual exceedance probability greater than about 0.1 (more frequent than a 10 year return period). A partial duration series analysis can be applied to the period of record data to improve the exceedance probability estimate for frequent events. A threshold is selected and all independent events above the threshold are extracted from the data. This accounts for the possibility of multiple statistically independent floods occurring within a single year.

The resulting data is sorted in descending order and ranked from 1 to n. The annual exceedance probability for each data value is computed using the following equation where M is the rank and n is the total number of years of data. An example of the approach is presented in Figure II-1-7.

$$AEP = 100 \frac{M}{n + 1}$$

USACE Approach for Developing Exceedance Curves

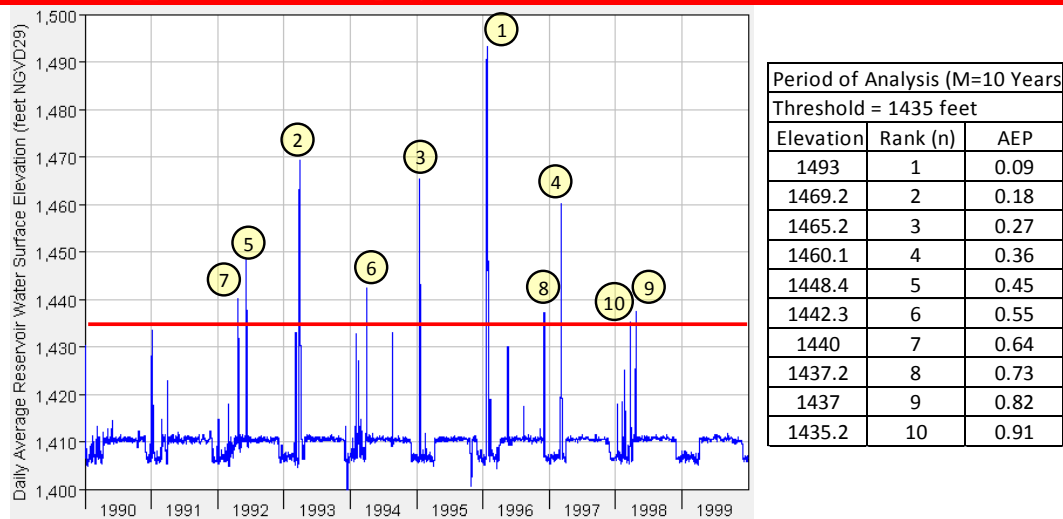


Figure II-1-7. Partial Duration Series

Figure II-1-8 illustrates a situation in which ignoring the partial duration series approach can significantly under represent the magnitude of frequent flood events. A reservoir stage of about 1440 feet would be expected to occur about once each year on average based on historic observations and the partial duration series analysis. The annual series analysis would indicate a much less frequent (and incorrect) recurrence interval of about once every two years for the 1440 feet stage.

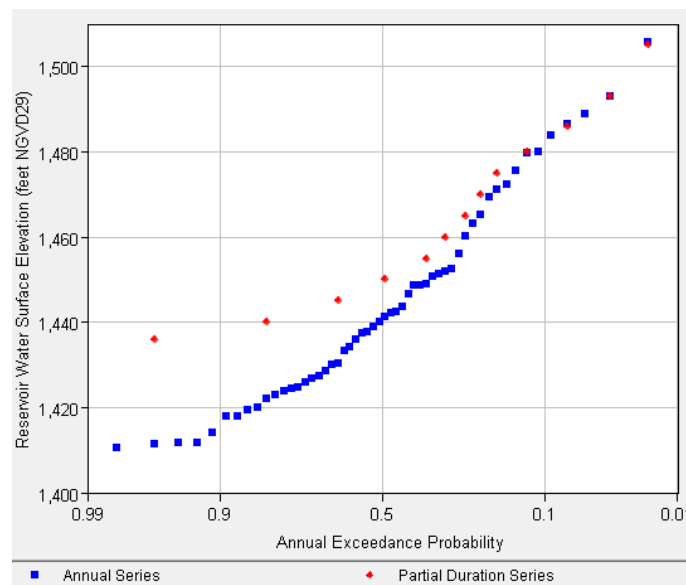


Figure II-1-8. Comparison Between Annual and Partial Duration Series

Extrapolation

The range of frequency represented by the period of record annual exceedance probability relationship is constrained by the length of the period of analysis. In most cases, this is an insufficient range to support a dam or levee safety risk analysis and extrapolation of the relationship is needed.

Exceedance probability relationships can be extrapolated based on routing hydrographs obtained

USACE Approach for Developing Exceedance Curves

from hydrologic models, routing representative hydrograph shapes having volumes consistent with the volume frequency relationships, or other appropriate methods. Routing of the hydrographs is an important step particularly for dams with controlled (i.e. gated) spillways because operation of the project discharge facilities can significantly influence the shape of the resulting stage frequency relationship. Routing assumptions should be consistent with the conditions the risk analysis is intended to represent. A common assumption is that the dam or levee is operated as authorized and intended. Other assumptions (e.g. IRRMs are in place) may be appropriate depending on the type of risk analysis.

Frequency based precipitation can be applied to a hydrologic model to obtain a hydrograph. The hydrograph can then be routed to obtain corresponding water surface stages and/or profiles. It may be reasonable to assume that the frequency of the rainfall approximately corresponds to the frequency of the resulting water surface stages. The risk analyst should recognize that this assumption is not always reasonable and appropriate adjustments should be made as needed.

Representative hydrograph shapes based on historic events, design events, or balanced hydrograph methods can be developed and scaled using the inflow volume frequency relationship and then routed to obtain corresponding water surface stages and/or profiles. It may be reasonable to assume that the frequency of the inflow volume approximately corresponds to the frequency of the resulting water surface stages. Again, this assumption may not be valid in every situation.

With either method, selecting an appropriate duration for the rainfall and/or inflow volume is an important decision. The selected duration should be representative of floods that are typical within the watershed.

For the previous example, both the frequency based rainfall approach and the volume based hydrograph approach have been implemented. For the frequency based rainfall approach, balanced rainfall hyetographs were developed from published precipitation depth-duration-frequency relationships in NOAA Atlas 14. Point rainfall amounts were spatially distributed using the ellipse pattern and area reduction factors in Hydrometeorological Report 52. The resulting rainfall distribution was then applied to an existing hydrologic model of the reservoir watershed to obtain inflow hydrographs. The inflow hydrographs were routed through the reservoir to obtain a peak stage estimate with an exceedance probability assumed to be equal to the exceedance probability for the corresponding rainfall.

For the volume hydrograph approach, an existing flood hydrograph shape was selected. The hydrograph was scaled to achieve a range of inflow volumes. An existing volume-duration frequency relationship was used to estimate the annual exceedance probability for each hydrograph volume. The hydrographs were routed through the reservoir to obtain corresponding peak stages with exceedance probabilities assumed to be equal to the exceedance probability for the corresponding inflow volume.

Results of the analyses are summarized in Figure II-1-9. A suggested composite exceedance probability relationship is drawn through the data based on judgment.

USACE Approach for Developing Exceedance Curves

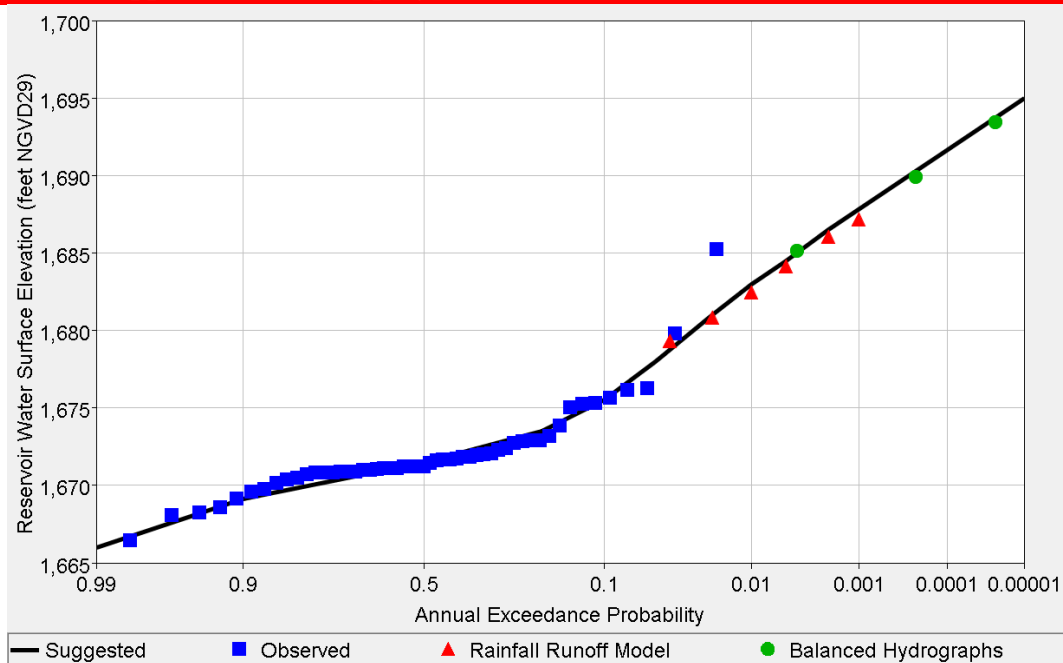


Figure II-1-9. Composite Exceedance Probability Relationship

Antecedent Conditions

When developing relationships for the annual chance exceedance of reservoir stage, the typical procedure requires the routing of hydrographs to obtain peak water surface stages and/or profiles. Consideration of the possible antecedent conditions that could exist at the start of these routings may be an important factor to consider when developing the annual exceedance probability relationship. Experience has demonstrated that a series of one or more hydrologic events can consume a significant portion of the storage in a reservoir or floodplain before the beginning of a significant hydrologic event.

The National Weather Service has conducted site specific antecedent storm investigations at various locations. A summary of the techniques applied in these studies can be found in Hydrometeorological Report 56. The general approach involves the analysis of historic storms to obtain an estimate for an antecedent event that can reasonably be expected to occur. The use of design events to establish antecedent conditions is not recommended for risk analysis. In some cases, peak water surface stages are not very sensitive to antecedent assumptions. In these cases, it is not necessary to spend a significant amount of effort. A screening evaluation looking at the sensitivity of peak stages to antecedent conditions should usually be sufficient.

Event Trees

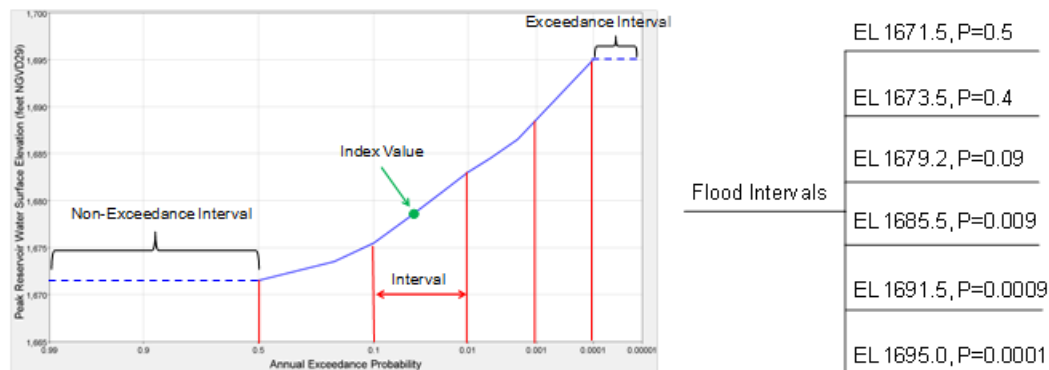
Because the exceedance probability relationship is a complementary cumulative distribution, probabilities for reaching specific peak water surface stages are equal to zero. As a result, partitions of water surface stage with a representative index value are needed for the event tree. The probability for an interval can be computed as the difference between the exceedance probabilities at the upper and lower bounds of the interval. The interval concept is illustrated in Figure II-1-10. The risk analyst needs to make a decision on the number of intervals needed to obtain the desired degree of numerical precision. The intervals do not have to be equal in size and do not have to be on a linear scale. The summation for the probabilities across all of the intervals is equal to 1.0 which satisfies the axioms of probability and is consistent with event tree rules. If the intervals are developed properly, the summation will always be 1.0 regardless of the number of

USACE Approach for Developing Exceedance Curves

intervals.

Failure to apply event intervals properly results in a ‘double counting’ which means that the probabilities associated with the flood events are accounted for multiple times in the event tree. This typically occurs when exceedance probabilities are used instead of interval probabilities. As a result, the summation of the loading probabilities across all loading branches of the event tree (assuming the event tree branches are collectively exhaustive) will be greater than 1.0. The summation will also vary with the number of intervals. Improper intervals can introduce significant errors in the risk estimate.

The intervals should also consider a non-exceedance and exceedance interval. The non-exceedance interval can be established based on a threshold loading below which the probability of failure and consequences are negligible. This becomes the bottom end of the lowest load range for which risks are estimated. The lower bound for the non-exceedance interval should be an annual exceedance probability of 1 and the upper bound should be defined by the threshold event. While simple in concept, the selected threshold value can have a significant influence on the estimated risks. Sensitivity analysis is suggested to evaluate whether refinement of the selected threshold is needed. The exceedance interval establishes the largest loading condition for which risks are estimated. It is important to assess whether or not there are any significant risks attributable to extreme loading that may be associated with high probabilities of failure. Would the risk significantly change if an additional higher loading interval was added to the analysis? The lower bound for the exceedance interval is the threshold for the largest loading that will be considered and the upper bound should be an annual exceedance probability of zero.



Elevation			Probability		
Lower Bound	Upper Bound	Index Value	Lower Bound	Upper Bound	Probability
n/a	1671.5	1671.5	1	0.5	0.5
1671.5	1675.5	1673.5	0.5	0.1	0.4
1675.5	1683.0	1679.2	0.1	0.01	0.09
1683.0	1688.0	1685.5	0.01	0.001	0.009
1688.0	1695.0	1691.5	0.001	0.0001	0.0009
1695.0	n/a	1695.0	0.0001	0	0.0001

Figure II-1-10. Peak Flood Stage Intervals for Event Tree Construction

Exceedance Duration

When a non-flood event (e.g. seismic) imparts a load on a dam or levee, the risk analyst needs to consider the coincident hydraulic load conditions (typically water surface stage) that can exist when the non-flood event occurs. The combination of the load imparted by the non-flood event

USACE Approach for Developing Exceedance Curves

and the coincident hydraulic load are then considered jointly in the development of other event tree inputs (e.g. system response functions). It is important to recognize that the coincident water surface stage is a random variable in the risk analysis. The risk analyst needs to estimate a reasonable range of possible coincident water surfaces stages along with their associated conditional probabilities [e.g. $P(\text{Stage}|\text{Earthquake})$] for inclusion in the event tree. This can be accomplished using an exceedance duration relationship which characterizes the percentage of time that a random variable (e.g. water surface stage) exceeds a specified value. It is important to understand that an exceedance duration relationship is not a true probability distribution for water surface stage. It cannot be used to obtain an annual probability. The exceedance duration relationship is used to infer the conditional probability of obtaining a value (e.g. water surface stage) coincident with another independent non-flood event (e.g. seismic).

An annual exceedance duration relationship is usually sufficient; however, exceedance duration relationships can also be developed conditional on a particular time period (e.g. monthly or seasonal). This is not typical for most dam or levee safety risk analysis. An example where it might be needed would be when winds associated with seasonal hurricane events are combined with a coincident water surface stage to produce a wave loading on the dam or levee.

Period of Record Analysis

The first step in developing a stage duration relationship involves collecting, assembling, and reviewing the period of record data. This process is similar to that used for developing exceedance probability relationships. The reader is referred to the exceedance probability section of this chapter for more information on data acquisition and review. An example data set showing daily average reservoir stages for a dam is presented in Figure II-1-11. This is the same data set that was used for the exceedance probability example with corrections having already being made for the missing and erroneous data.

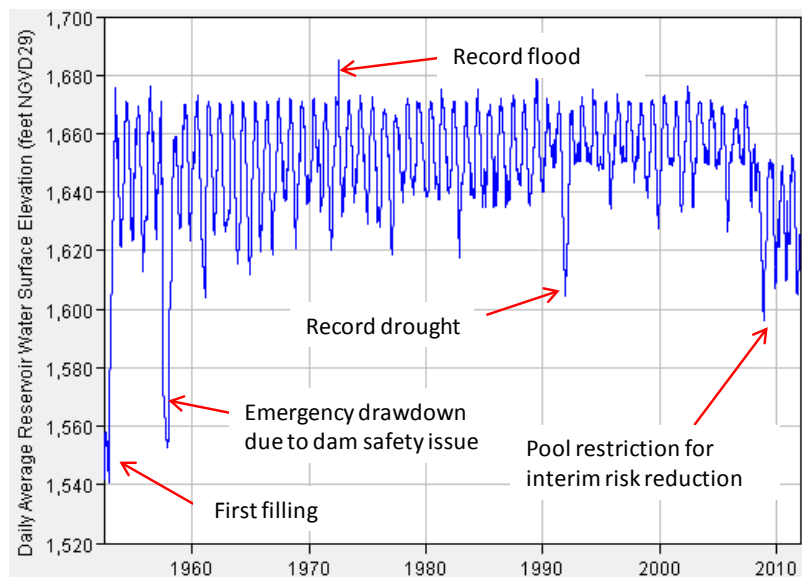


Figure II-1-11. Daily Average Reservoir Stage Data

Once data quality issues have been addressed, development of the duration relationship can proceed. The second step involves calculation of the duration relationship. A period of analysis is selected based on the nature of the data and the needs of the risk analysis. A minimum period of 10 years is recommended to provide a reasonable estimate of the duration relationship for duration values greater than about 0.1%. Longer periods of analysis should be used if data is readily available and the data is consistent with the operating conditions assumed for the purposes of the

USACE Approach for Developing Exceedance Curves

risk analysis. For this example, the period from 1997 through 2006 has been selected as being representative of normal operation in accordance with the authorized water control plan. The duration relationship is then computed by sorting the data values for the adopted period of analysis in descending order, ranking the sorted data values from 1 to n, and computing the percent of time exceeded for each data value using the following equation where M is the rank and n is the total number of data values.

$$D(\%) = 100 \frac{M}{n + 1}$$

A binning approach can also be used to develop the duration relationship from the data. (USACE, 1996).

The computations needed to develop duration relationship can be accomplished using a spreadsheet. USACE recommends using either the HEC-SSP or HEC-DSSVue software packages (<http://www.hec.usace.army.mil>).

The resulting duration relationship for the sample data set is presented graphically in Figure II-1-12 with a tabulation of the duration values.

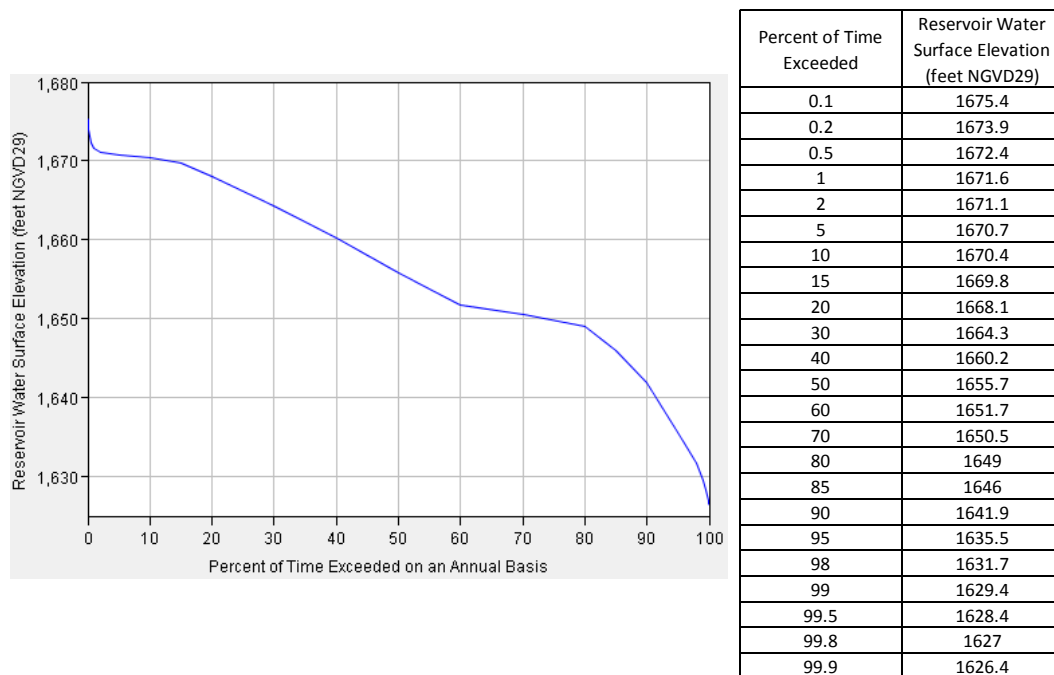


Figure II-1-12. Example Duration Relationship

Extrapolation

Duration relationships may need to be extrapolated in cases where the period of record is too short and/or the risk associated with non-flood loading events is significant due to high consequences or other factors. This can be accomplished by routing representative discharge hydrographs for a range of frequency based inflow volumes or by performing a stochastic simulation. The resulting synthetic stage hydrographs can be analyzed to infer a duration relationship.

USACE Approach for Developing Exceedance Curves

Event Trees

Conditional event tree probabilities associated with the water surface stages that are coincident with a non-flood event can be derived from the duration relationship. Because the duration relationship is analogous to a complementary cumulative distribution, probabilities for specific water surface stages are equal to zero. As a result, partitions of water surface stage with a representative index value are needed for the event tree. The probability for an interval can be computed as the difference between the exceedance duration at the upper and lower bounds of the interval. The interval concept is illustrated in Figure II-1-13. The risk analyst needs to make a decision on the number of intervals needed to obtain the desired degree of numerical precision. The intervals do not have to be equal in size and do not have to be on a linear scale.

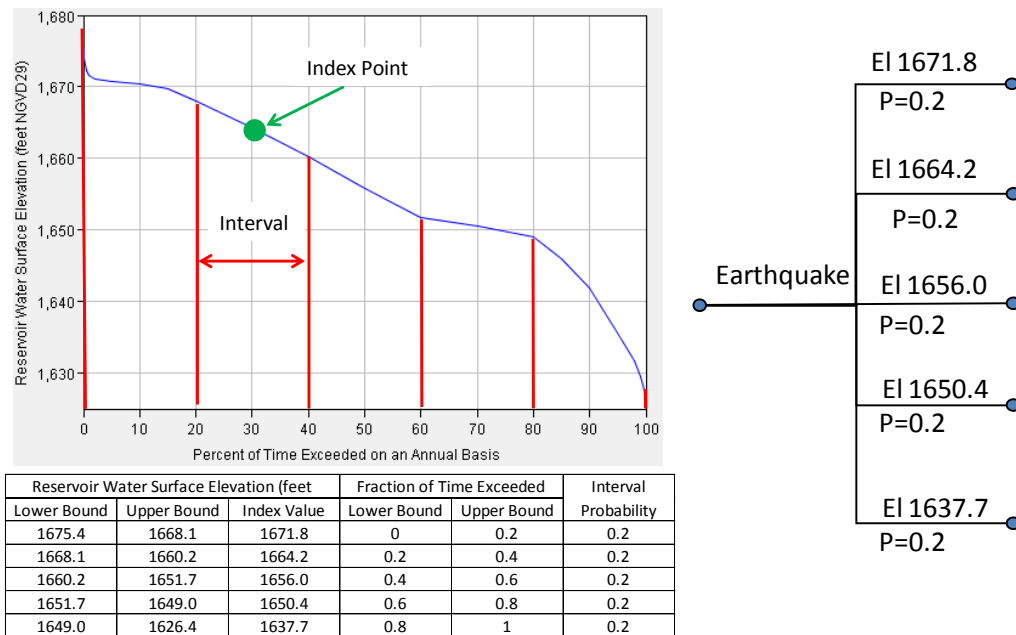


Figure II-1-13. Developing Duration Intervals for the Event Tree

Failure to apply event intervals properly results in a 'double counting' error which means that the probabilities associated with the flood events are accounted for multiple times in the event tree. This typically occurs when exceedance probabilities are used instead of interval probabilities. As a result, the summation of the loading probabilities across all loading branches of the event tree (assuming the event tree branches are collectively exhaustive) will be greater than 1.0. The summation will also vary with the number of intervals. Improper intervals can introduce significant errors in the risk estimate.

Uncertainty

Flood loading relationships include both aleatory and epistemic uncertainties. The frequency relationship itself models the random (aleatory) uncertainty associated with flood events. The epistemic (knowledge) uncertainty is modeled by the confidence bounds about the frequency relationship. Methods exist to estimate the epistemic uncertainty component for flood loading relationships; however, USACE has not routinely included these uncertainties in risk analyses for dam and levee safety. Epistemic uncertainties associated with discharge and volume can be estimated using established methods such as those found in Bulletin 17B. Epistemic uncertainties associated with stage can be estimated using methods such as those found in EM 1110-2-1619.

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Exercise

The maximum reservoir elevation has been captured for the past 10 years of record and is listed in Table II-1-1. On an annual basis, what is the likelihood of the reservoir being in the range from Elevation 2415 to Elevation 2440?

Table II-1-1. Example annual maximum reservoir elevation data

Calendar Year	Maximum Water Surface Elevation (ft)
1999	2431.52
2000	2388.10
2001	2440.94
2002	2415.00
2003	2425.75
2004	2440.04
2005	2443.79
2006	2413.35
2007	2440.38
2008	2440.71

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